# Radio Pulsar Timing for GLAST Requirements, Costs and Triage

**Good ephemerides will dramatically enhance pulsar (and PWN) science**

# Basic Quest

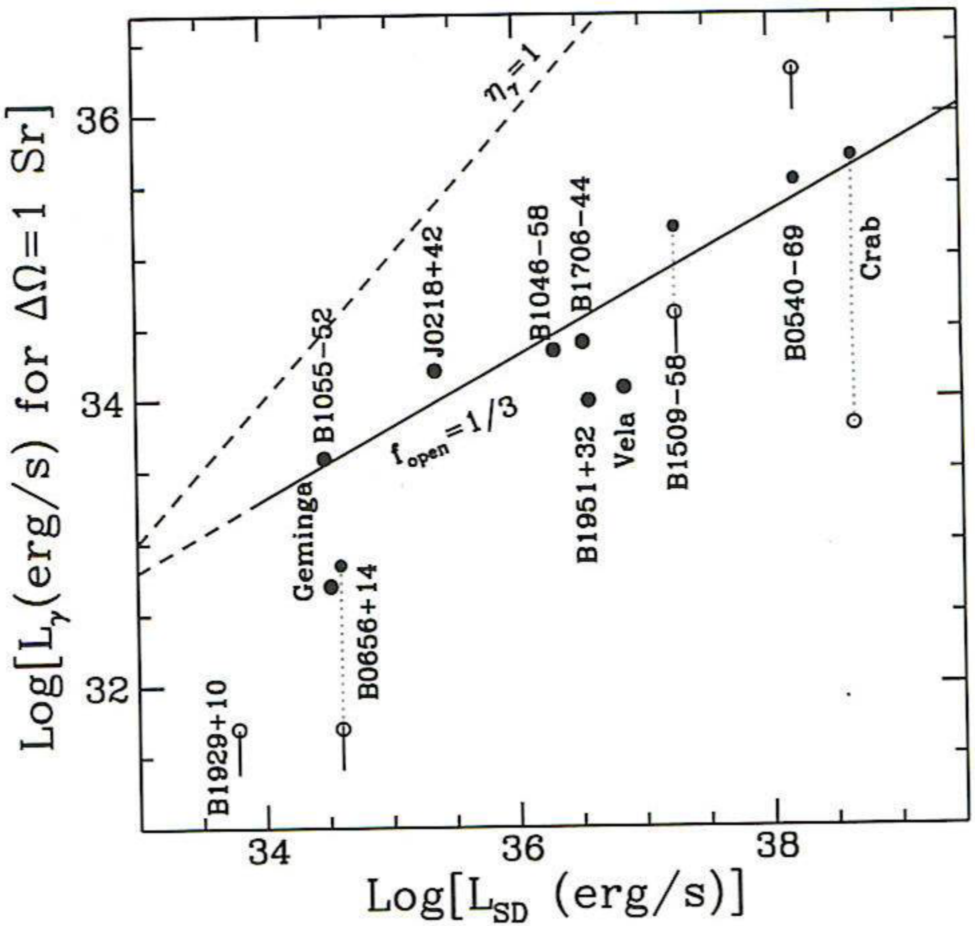
- **Maintain Ephemerides for known pulsars at an accuracy which does not 'blur' significantly light curves, phase-resolved spectra, etc.**
  - **Two generic classes of high Edot PSR: Young, MSP**
  - **Good DM for absolute phases, comparison with multi-$\nu$**
    - **For a few PSR e.g. Crab, DM needs to be monitored – no big problem**
    - **May also be useful to have good accuracy RM for absolute PA comparisons, Pol'n diagnostics – ~constant, can be obtained later**
  - **Young PSR (dominated 3EG sky) have large timing noise, occasional large glitches**
    - **Timing Noise – spectrum of rotational instabilities, slowly growing $\delta\phi$.**
    - **'Glitches' – large events $d\nu/\nu$ up to $10^{-6}$. Lose phase solution**
- **Minimize telescope time to maintain this data set**
- **Encourage coordination of international resources, ensure that tough, but important PSR, do not fall through the gaps**
  - **Steve Thorsett will likely be helping, but not too early to discuss….**

# Basic Assumptions

- Timing at L band (~1.4 GHz)
  - Appropriate to many distant young PSR – mitigate scattering
- Will assume that we want to keep up with timing noise
  - Will not assume dense coverage of rare large 'glitches'
  - Note this means that if cadence for some pulsars is 1-2/yr will lose up to ~1yr of γ-ray photon stats – acceptable in 5yr mission
  - A few PSR ARE monitored for glitches (Crab– Jodrell, Vela – Hobart), get the glitch-response γ-ray physics (if any!) from these.
- Our goal should be to get $\delta t < 1\mathrm{mP}\,(f_{Vel}/f_{\gamma})^{1/2}$
  - Only brighter PSR need better than ~20mP
  - Minimum 20mP ephemeris for any useful timing
  - Minimum 5m/PSR/visit for large telescopes (settle, etc)

# Gamma-ray Assumptions

- **Most Gap voltage drop-limited models predict $f_\gamma \sim \mathrm{Edot}^{1/2}/d^2$:**
- **Notice that high energy efficiency $\eta_\gamma \sim \mathrm{Edot}^{-1/2}$**
  - **Efficiency saturates at some `Death line' Edot**
  - **Edot ~$10^{30}$ erg/s (Radio → polar cap surface gap?)**
  - **Edot ~$10^{34}$ erg/s ($\gamma$-ray → higher altitude gap)**
- **Beaming is critical!**
  - **difficult to predict w/o magnetic inclination angles $\alpha$, $\beta$**
  - **Eg. Note B0656+14 much fainter than correlation, J00218+42 brighter**



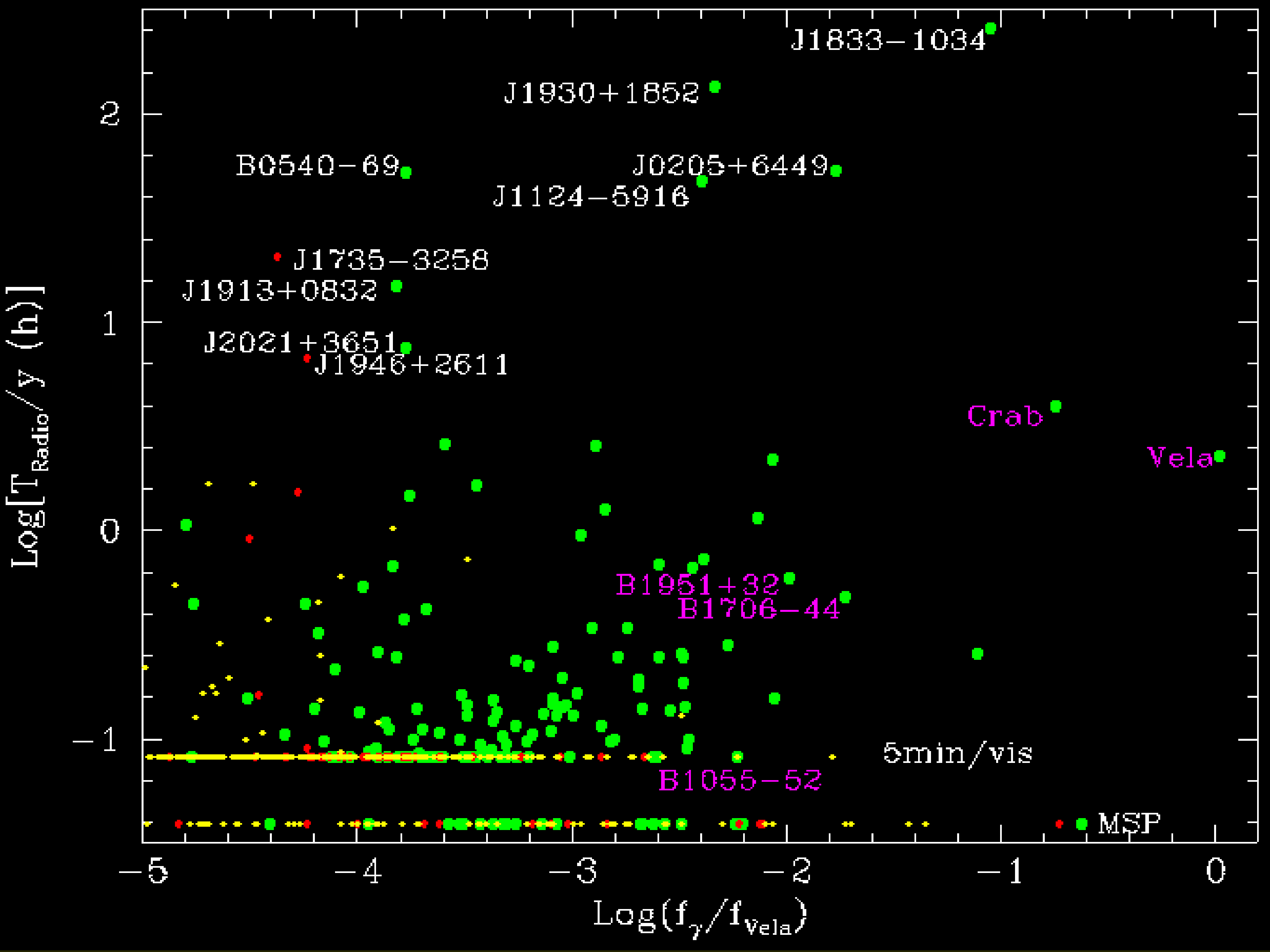
# Radio Timing Assumptions

- Use ATNF database to survey pulsars
- Use $S_{1.4}$ – when only $S_{0.4}$ available scale as $\nu^{-2.5}$
  - Fairly conservative, some system better below GHz, eg. GBT
- Narrow pulses give higher S/N
- -- toa accuracy: $\delta\phi \sim (W/P)^{1.5}\, S_{1.4}/(t_{obs})^{1/2}$
  - Scale to ~3hr to get J0205 on GBT i.e. hours of 100m-class time
  - In detail, depends on back-ends, of course
  - Floor of ~300s to check any source
- Timing Noise – assume frequency noise, use Pdot to estimate activity parameter:
- Residual grows as $\phi_{rms} \sim [10^{\Delta 8}/P](t/10^8 s)^{2/3}$
  - Where $\Delta_8$ = 6.6+0.6 Log (Pdot) (Arzoumanian, Nice & Thorsett 94)
- Gives max time between visits
- Derive total `required time' in hrs/yr

| i | name | fvel | srad | ledot | treq | vpery | tpery | tot | |
|---|---|---|---|---|---|---|---|---|---|
| 1 | B0833-45 | 1.041 | 1100 | 36.84 | 1.31e-07 | 27.6 | 2.3 | 2.3 | |
| 2 | J0633+1746 | 0.2365 | 0.01 | 34.51 | 2.772e+04 | 3.33 | 0 | 2.3 | |
| 3 | B0531+21 | 0.1787 | 14 | * | 0.007967 | 48.41 | 4.034 | 6.334 | |
| 4 | J1833-1034 | 0.08767 | 0.07 | 37.53 | 13.88 | 18.75 | 260.2 | 266.5 | |
| 5 | B0656+14 | 0.07726 | 3.7 | 34.58 | 0.007226 | 3.161 | 0.2634 | 266.8 | |
| 6 | B1706-44 | 0.01856 | 7.3 | 36.53 | 0.0008194 | 5.855 | 0.4879 | 267.3 | |
| 7 | J0205+6449 | 0.01691 | 0.04 | 37.43 | 5.318 | 10.24 | 54.46 | 321.7 | 3C58 |
| 8 | B1951+32 | 0.01026 | 1 | 36.57 | 0.2021 | 2.999 | 0.6059 | 322.3 | |
| 9 | J1740+1000 | 0.008643 | 9.2 | 35.37 | 0.001197 | 1.927 | 0.1606 | 322.5 | |
| 10 | J1747-2958 | 0.008501 | 0.25 | 36.4 | 0.5666 | 3.918 | 2.22 | 324.7 | |
| 11 | J1909-3744 | 0.007353 | 0.01 | 34.33 | 861.7 | 0.08587 | -0.001 | 324.7 | |
| 12 | B1509-58 | 0.007305 | 0.94 | 37.25 | 0.116 | 10.19 | 1.183 | 325.9 | |
| 13 | J2043+2740 | 0.006178 | 0.8 | 34.75 | 0.1131 | 0.7617 | 0.1131 | [illegible] | Cyg Loop? w/ X-ray |
| 14 | J0034-0534 | 0.006012 | 0.61 | 34.47 | 14.66 | 0.07164 | -0.001 | 326 | |
| 15 | B0355+54 | 0.005844 | 23 | 34.66 | 2.008e-06 | 0.8885 | 0.08333 | 326.1 | |
| 16 | B1957+20 | 0.005696 | 0.35 | 35.2 | 0.005629 | 0.1273 | -0.001 | 326.1 | |
| 17 | B1046-58 | 0.005308 | 6.5 | 36.3 | 0.0001367 | 3.453 | 0.2877 | 326.4 | |
| 18 | J1930+1852 | 0.004619 | 0.06 | 37.06 | 19.8 | 7.001 | 138.6 | 465 | G54.1+0.3 |
| 19 | J1524-5625 | 0.004044 | 0.83 | 36.51 | 0.2484 | 2.982 | 0.7406 | 465.7 | |
| 20 | J1124-5916 | 0.00396 | 0.08 | 37.08 | 7.251 | 6.688 | 48.49 | 514.2 | |
| 21 | J1357-6429 | 0.003614 | 0.44 | 36.49 | 0.1611 | 4.227 | 0.6809 | 514.9 | |
| 22 | B0740-28 | 0.003492 | 15 | 35.16 | 6.175e-06 | 1.225 | 0.1021 | 515 | |
| 23 | B0114+58 | 0.003414 | 0.3 | 35.34 | 0.02935 | 1.111 | 0.09254 | 515.1 | |
| 24 | J1531-5610 | 0.003309 | 0.6 | 35.96 | 0.0352 | 1.748 | 0.1457 | 515.3 | |
| 25 | B1823-13 | 0.003286 | 2.1 | 36.45 | 0.001631 | 3.04 | 0.2533 | 515.5 | |
| 26 | J1809-1917 | 0.003249 | 2.5 | 36.25 | 0.06271 | 2.253 | 0.1878 | 515.7 | |
| 27 | J1617-5055 | 0.003195 | 0.01 | 37.2 | 219 | 4.905 | 0 | 515.7 | |
| 28 | B1800-21 | 0.003185 | 7.6 | 36.35 | 0.0007433 | 3.157 | 0.2631 | 516 | |
| 29 | J1913+1011 | 0.002828 | 0.5 | 36.46 | 0.02652 | 1.671 | 0.1392 | 516.1 | |
| 30 | B1937+21 | 0.002698 | 16 | 36.04 | 3.265e-05 | 0.2103 | -0.001 | 516.1 | |
| 31 | B1757-24 | 0.002529 | 0.85 | 36.41 | 0.01862 | 3.002 | 0.2502 | 516.3 | |
| 32 | J0940-5428 | 0.00252 | 0.35 | 36.29 | 0.3179 | 2.208 | 0.7018 | 517 | |
| 33 | B1055-52 | 0.002466 | 3.478 | 34.48 | 0.0008677 | 0.6423 | 0.08333 | 517.1 | |
| 34 | J1740-5340 | 0.002358 | 0.01 | 35.13 | 293 | 0.1403 | -0.001 | 517.1 | |
| 35 | J0538+2817 | 0.002355 | 1.9 | 34.69 | 5.445e-05 | 0.6606 | 0.08333 | 517.2 | |
| 36 | J1549-4848 | 0.002132 | 0.47 | 34.37 | 0.001256 | 0.7095 | 0.08333 | 517.3 | |
| 37 | J1718-3825 | 0.002114 | 1.3 | 36.1 | 0.00247 | 1.699 | 0.1416 | 517.4 | |
| 38 | J1843-1113 | 0.002104 | 0.1 | 34.78 | 7.277 | 0.07038 | -0.001 | 517.4 | |
| 39 | B1821-24 | 0.002059 | 0.18 | 36.35 | 0.1071 | 0.3909 | -0.001 | 517.4 | |
| 40 | B1727-33 | 0.002022 | 3.2 | 36.09 | 0.0006709 | 2.357 | 0.1964 | 517.6 | |
| 41 | B1853+01 | 0.002007 | 0.19 | 35.63 | 0.002328 | 2.187 | 0.1822 | 517.8 | |
| 42 | J1420-6048 | 0.001782 | 0.9 | 37.02 | 0.09179 | 3.768 | 0.3459 | 518.2 | |
| 43 | J1509-5850 | 0.00164 | 0.15 | 35.71 | 0.1923 | 1.308 | 0.2515 | 518.4 | |
| 44 | J1739-3023 | 0.00157 | 1 | 35.48 | 0.004445 | 1.207 | 0.1005 | 518.5 | |
| 45 | J1835-1106 | 0.001491 | 2.2 | 35.25 | 0.0001376 | 1.193 | 0.09941 | 518.6 | |
| 46 | B1259-63 | 0.001426 | 1.7 | 35.92 | 1.132 | 1.135 | 1.284 | 519.9 | |

# Observability predictions

- **Safest: stick w/ > $2x10^{34}$ erg/s**
  - **But get a good sample beyond this – tend to be stable, can likely recover γ-ray light curve from low cadence timing**
- **Several predicted bright PSR *NOT* 3EG sources**
  - **Emission physics?**
  - **Beaming geometry?**
- **Remember observed parameter uncertainties**
  - **DM distances 30% errors**
  - **Edot for GC MSP**
  - **Beaming corrections**
  - **Background issues.**


J1833−1034
J1930+1852
B0540−69
J0205+6449
J1124−5916
J1735−3258
J1913+0832
J2021+3651
J1946+2611
Crab
Vela
B1951+32
B1706−44
5min/vis
B1055−52
MSP
Log[$T_{Radio}$/y (h)]
Log($f_\gamma/f_{Vela}$)
2
1
0
−1
−5
−4
−3
−2
−1
0

# Cumulative Required time

- **Time required to get the Camillo PSRs dominates!**
- **143 PSR >$10^{-4} f_{Vela}$, log(Edot)>34.3**
  - **615h/year → 401h for 4 energetic PWN (Camillo) PSR!**
- **170 (Log Edot > 34),**
- **244 (Log Edot> 33.5),**
- **293 (Log Edot> 33)**
- **X-ray timing?**
  - **RXTE?**
  - **Indian ASTROSAT?**

# Ephemeris Resources

- **Foundations**
  - Parkes 64m – Simon Johnston (+Manchester, Bailes, etc)
  - Jodrell 76m – Michael Kramer (+Lyne, etc)
  - Key issue – these major efforts will need direct personnel support from GLAST!! GS level likely best to man telescopes, esp. Parkes
- **Other Big Guns**
  - GBT 100m– Ransom?, Camillo?, Backer?
  - Arecibo 305m– Cordes? Thorsett?, Nice?
  - Nancay ~70m– Smith, Cognard
- **Smaller Focused Efforts**
- **Longer shots**
  - GMRT ~250m
  - ATA ~115m
  - KAT ~65m

# Special Focus on 3EG coincidences

## 30 PSR coincident w/ Unidentified 3EG sources – Alice Harding

| 1 | 3EG | PSR | P | Pdot | d(kpc) | Age (yr) | $B_0$ | $L_{SD}$ | $L_{SD}/d^2$ | Notes | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 2 | 3EGJ1013-5915 | J1016-5857 | 0.107379757 | 8.06E-14 | 7.55 | 2.11E+04 | 5.96E+12 | 2.57E+36 | 3.13E+10 | Chandra PWN+pt src | |
| 3 | 3EGJ1014-5705 | J1015-5719 | 0.139881678 | 5.74E-14 | 4.88 | 3.86E+04 | 5.74E+12 | 8.27E+35 | 2.41E+10 | No X-ray. | |
| 4 | 3EGJ1102-6103 | J1104-6103 | 0.280905302 | 1.97E-15 | 1.94 | 2.26E+06 | 1.51E+12 | 3.50E+33 | 6.46E+08 | | |
| 5 | 3EGJ1102-6103 | J1105-6107 | 0.063192942 | 1.58E-14 | 4.91 | 6.33E+04 | 2.03E+12 | 2.48E+36 | 7.13E+10 | Chandra, no PWN or p | |
| 6 | 3EGJ1410-6147 | J1412-6145 | 0.315224971 | 9.87E-14 | 7.68 | 5.06E+04 | 1.13E+13 | 1.24E+35 | 1.46E+09 | | |
| 7 | 3EGJ1410-6147 | J1413-6141 | 0.28562462 | 3.33E-13 | 9.92 | 1.36E+04 | 1.98E+13 | 5.65E+35 | 3.99E+09 | 8.1 arcmin from J1412 | |
| 8 | 3EGJ1420-6038 | J1420-6048 | 0.068179877 | 8.32E-14 | 5.56 | 1.30E+04 | 4.82E+12 | 1.04E+37 | 2.33E+11 | | |
| 9 | 3EGJ1639-4702 | J1637-4642 | 0.154027428 | 5.92E-14 | 5.01 | 4.12E+04 | 6.12E+12 | 6.40E+35 | 1.77E+10 | No X-ray. | |
| 10 | 3EGJ1639-4702 | J1640-4715 | 0.517404835 | 4.20E-14 | 6.31 | 1.95E+05 | 9.45E+12 | 1.20E+34 | 2.09E+08 | | |
| 11 | 3EGJ1639-4702 | J1638-4608 | 0.278 | 5.15E-14 | 5.166 | 8.80E+04 | 7.66E+12 | 9.47E+34 | 2.46E+09 | | |
| 12 | 3EGJ1714-3857 | J1713-3949 | 0.392 | 6.00E-14 | 4.3236 | 1.07E+05 | 9.82E+12 | 3.93E+34 | 1.46E+09 | | |
| 13 | 3EGJ1714-3857 | J1715-3903 | 0.278481055 | 3.77E-14 | 4.07 | 1.17E+05 | 6.56E+12 | 6.89E+34 | 2.89E+09 | | |
| 14 | 3EGJ1734-3232 | J1734-3333 | 1.169 | 2.28E-12 | 6.4712 | 8.35E+03 | 1.04E+14 | 5.59E+34 | 9.28E+08 | | |
| 15 | 3EGJ1734-3232 | J1735-3258 | 0.351 | 2.60E-14 | 9.5814 | 2.19E+05 | 6.12E+12 | 2.38E+34 | 1.80E+08 | | |
| 16 | 3EGJ1736-2908 | J1739-2903 | 0.322882432 | 7.88E-15 | 2.45 | 6.49E+05 | 3.23E+12 | 9.24E+33 | 1.07E+09 | | |
| 17 | 3EGJ1744-3011 | J1745-3040 | 0.367 | 1.07E-14 | 1.9133 | 5.61E+05 | 4.00E+12 | 8.48E+33 | 1.61E+09 | | |
| 18 | 3EGJ1746-1001 | J1745-0952 | 0.019376303 | 9.50E-20 | 1.8 | 3.23E+09 | 2.75E+09 | 5.16E+32 | 1.10E+08 | | |
| 19 | 3EGJ1746-2851 | J1747-2958 | 0.099 | 6.14E-14 | 2.0079 | 2.62E+04 | 5.00E+12 | 2.53E+36 | 4.37E+11 | Mouse | |
| 20 | 3EGJ1800-2338 | J1801-2451 | 0.125 | 1.27E-13 | 5.2182 | 1.59E+04 | 8.10E+12 | 2.60E+36 | 6.64E+10 | W28 | |
| 21 | 3EGJ1824-1514 | J1825-1446 | 0.279186875 | 2.27E-14 | 4.96 | 1.95E+05 | 5.10E+12 | 4.11E+34 | 1.16E+09 | | |
| 22 | 3EGJ1837-0423 | J1838-0453 | 0.380830777 | 1.16E-13 | 7.93 | 5.22E+04 | 1.34E+13 | 8.27E+34 | 9.13E+08 | | |
| 23 | 3EGJ1837-0606 | J1837-0559 | 0.201062574 | 3.30E-15 | 5.37 | 9.64E+05 | 1.65E+12 | 1.61E+34 | 3.87E+08 | | |
| 24 | 3EGJ1837-0606 | J1837-0604 | 0.096294208 | 4.52E-14 | 6.28 | 3.38E+04 | 4.22E+12 | 2.00E+36 | 3.52E+10 | ASCA: 2001ApJS..133 | |
| 25 | 3EGJ1856+0114 | J1856+0113 | 0.26743961 | 2.08E-13 | 3.3 | 2.03E+04 | 1.51E+13 | 4.30E+35 | 2.74E+10 | W44 | |
| 26 | 3EGJ1903+0550 | J1905+0616 | 0.989707063 | 1.35E-13 | 5.72 | 1.16E+05 | 2.34E+13 | 5.51E+33 | 1.17E+08 | | |
| 27 | 3EGJ1928+1733 | J1930+1852 | 0.136 | 7.50E-13 | 5 | 2.95E+03 | 2.00E+13 | 1.13E+37 | 3.14E+11 | | |
| 28 | 3EGJ1928+1733 | J1928+1746 | 0.06872878 | 1.32E-14 | 5.8 | 8.67E+04 | 1.93E+12 | 1.61E+36 | 3.32E+10 | No X-ray. | 2005astro.p |
| 29 | 3EGJ1958+2909 | J1957+2833 | 0.308 | 3.12E-15 | 5.587 | 1.60E+06 | 2.00E+12 | 4.31E+33 | 9.59E+07 | | |
| 30 | 3EGJ2227+6122 | J2229+6114 | 0.051623574 | 7.83E-14 | 7.22 | 1.05E+04 | 4.07E+12 | 2.25E+37 | 2.99E+11 | X-ray psr | |
| 31 | 3EGJ2021+3716 | J2021+3651 | 0.103722225 | 9.56E-14 | 12.13 | 1.72E+04 | 6.39E+12 | 3.38E+36 | 1.60E+10 | | |
| 32 | | | | | | | | | | | |

# New Objects

- **Deep Searches of 3EG regions, PWNe may yield a few more**
- **Some from ALFA (only Arecibo can handle these…)**
  - **Just checked J1928+1746 (=3EG J1928+1733?) – 50$^{th}$ needs 10min/yr**

# Strategy During GLAST mission

- **Initially get all > $10^{34}$ erg/s, selected set of nearby less energetic PSR**
  - **Estimate activity parameter after ~1yr, adjust cadence**
- **Adjust timing list during mission: Drop srcs w/ no n$\sigma$ detection after m years**
- **Add new PSR from deep searches of unidentified GLAST error boxes**